Hydrogeology of the Cenozoic Igneous Rocks, Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah

GEOLOGICAL SURVEY PROFESSIONAL PAPER 521-D

Prepared in cooperation with the Bureau of Indian Affairs and the Navajo Tribe

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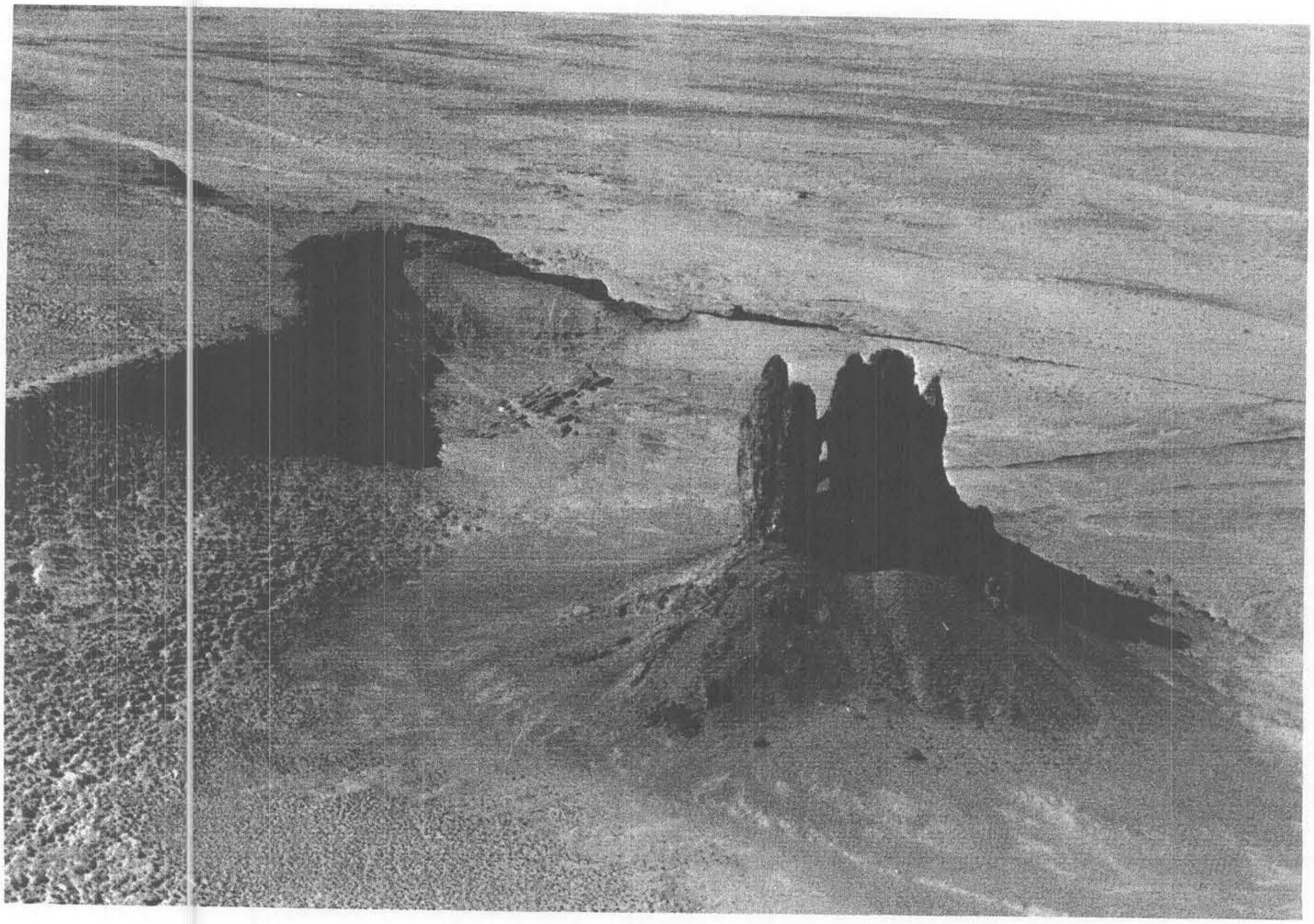

Boundary Butte, one of the isolated volcanic necks in the Navajo country. Photograph by E. T. Nichols.

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By J. P. AKERS, J. C. SHORTY, *and* P. R. STEVENS

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By J. P. Akers, J. C. Shorty, and P. R. Stevens

ABSTRACT

The igneous rocks exposed in widely separated areas in the Navajo and Hopi Indian Reservations are mainly of volcanic origin. Porphyritic rocks of laccolithic origin, however, are exposed in several places in the Carrizo Mountains and in a small outcrop on Navajo Mountain.

The volcanic rocks occur as flows, dikes, necks, cinder cones, and bedded tuff in fillings of diatremes and beneath some lava flows in volcanic fields that are grouped, according to composition, into three provinces—the monchiquite province centered in the Hopi Buttes area, the minette province in the northeastern part of the reservations, and the basalt province in the southwestern part of the reservations.

Stratigraphic and faunal evidence and potassium-argon age determinations indicate that the igneous rocks of the monchiquite province are of probable Pliocene age; those of the minette province have not been dated precisely but are believed to be older than those of the monchiquite province; and those of the basalt province are late Pliocene to late Holocene in age.

The volcanic rocks yield water to wells and springs. Most wells obtain water from the tuffaceous material that fills the diatremes, and most springs discharge from the bedded tuff beneath the lava flows. The diatremes are unique traps for the accumulation of ground water. The funnel-shaped structures have large recharge areas on the surface, which aid in the centripetal movement of water into the permeable materials that fill the orifices. Of the 14 test wells drilled into diatremes in the Hopi Buttes area, eight produced a sufficient quantity of potable water for domestic or stock use, three produced water of insufficient quantity or quality, and three were dry. The concentrations of dissolved solids in water from wells drilled in the diatremes range from 262 to 8,140 parts per million; water from the springs has concentrations ranging from 246 to 1,450 parts per million.

Additional development of water from the volcanic rocks is limited mainly to the diatremes that have not been explored in the Hopi Buttes. The amount and quality of water that may be obtained from a given diatreme, however, cannot be predicted.

INTRODUCTION

In the Navajo and Hopi Indian Reservations, the igneous rocks of Cenozoic age are mainly of volcanic origin, and they constitute less than 5 percent of the rocks exposed in the area. Most of the igneous rocks are composed of monchiquite, minette, or basalt and were emplaced in widely separated volcanic fields as lava flows, necks, dikes, cinder cones, bedded tuff, and some pyroclastics. Diorite porphyry, part of a stock-laccolith sequence, was intruded into the sedimentary rocks and is exposed in the Carrizo Mountains; syenite porphyry is exposed in a small area on Navajo Mountain.

The igneous rocks are important hydrologically only because they contain some ground water in areas where the sedimentary rocks are dry. The most important source of ground water in the igneous rocks is the tuffaceous and pyroclastic fillings of diatremes (funnel-shaped volcanic vents) and the bedded tuff beneath the lava flows. The diatreme from which Buell Park was formed supplies part of the water for the operation of the sawmill at Navajo, N. Mex. Although other diatremes in the Hopi Buttes are known to contain water, it is of poor chemical quality in many and is unfit for domestic or stock purposes. The tuff beds that underlie the basalt flows in the Hopi Buttes form a conspicuous spring horizon, and a few small springs discharge from the volcanic rocks in the Chuska Mountains and in the western San Juan basin.

PURPOSE, SCOPE, AND ORGANIZATION OF THE REPORT

The increasing need for dependable water supplies in the reservations is the result of an expanding Indian population and economy. Concurrent with this expansion, the drought, which started in about 1925 in the Southwest (Thomas, 1963), has become more severe. Because of the decreasing rainfall, surface and shallow subsurface water supplies have become less dependable, and many previously reliable sources have dried up in recent years.

In 1946 the U.S. Geological Survey, at the request of the Bureau of Indian Affairs, made a series of hydrologic investigations to help alleviate the water shortage in several places on the reservations. In 1950 the Geological Survey, in cooperation with the Bureau of Indian Affairs, began a comprehensive regional investigation of the geology and ground-water resources of the reservations. The principal objectives were to determine the feasibility of developing ground-water supplies for stock, institutional, and industrial uses in particular areas and at several hundred well sites scattered throughout the reservations and in adjoining areas owned by the Navajo Tribe; to inventory the wells and springs; to investigate the geology and ground-water hydrology; and to appraise the potential for future water development.

This report is the fourth chapter of Geological Survey Professional Paper 521, which describes the geology and hydrology of the reservations. The present report discusses only the igneous rocks of Cenozoic age. Stratigraphic descriptions of the uppermost Triassic and the Jurassic rocks have been published previously as Professional Paper 291 (Harshbarger and others, 1957). The basic geohydrologic data—records of wells and springs, selected chemical analyses, and selected drillers' logs, lithologic logs, and stratigraphic sections—are published separately as Arizona State Land Department Water-Resources Reports 12–A (Davis and others, 1963), 12–B (Kister and Hatchett, 1963), 12–C (Cooley and others, 1964), 12–D (Cooley and others, 1966), and 12–E (McGavock and others, 1966). The detailed geologic maps of the reservations and descriptions of the sedimentary features are included in Professional Paper 521–A (Cooley and others, 1969).

LOCATION

The Navajo Indian Reservation is in parts of Apache, Navajo, and Coconino Counties in northeastern Arizona; San Juan and McKinley Counties in northwestern New Mexico; and San Juan County in southeastern Utah (fig. 1). The Hopi Indian Reservation is in the central part of the Navajo Indian Reservation in Arizona. The reservations have an area of about 25,000 square miles, which is about three times the size of New Jersey.

In this report the term "Navajo country" (Gregory, 1917, p. 11) is used broadly to include the Navajo and Hopi Indian Reservations and the area lying principally between the Colorado, San Juan, and Little Colorado Rivers. The term "Hopi country" is an informal designation for the Hopi Indian Reservation. The reservations are divided by the Bureau of Indian Affairs into 18 administrative districts. Districts 1–5 and 7–18 constitute the Navajo Indian Reservation, and district 6 is the Hopi Indian Reservation (fig. 1). Few detailed maps of the reservations were available at the time of this study, but 15-minute planimetric maps compiled from aerial photographs were available. These maps are numbered arbitrarily from 1 to 151, starting in the upper right corner of the reservations and continuing from right to left in rows (fig. 1).

FIELDWORK

The geologic fieldwork consisted principally of mapping (at a scale of 2 inches equals 1 mile) and brief examinations of the volcanic outcrops. No new petrographic work was done, and much of the information on composition of the igneous rocks was obtained from reports by Robinson (1913), Gregory (1917), and Williams (1936). The hydrologic fieldwork consisted principally of an inventory of wells and springs, well tests, and the collection of water samples for chemical analyses. Nearly all the new wells drilled in the volcanic rocks were tested to determine the yield and amount of drawdown from the static water level. The well tests, except those in Buell Park, involved only the pumping well because nearby observation wells were not available.

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The writers are grateful for the assistance, cooperation, and information given by the late J. J. Schwartz, former head of the Bureau of Indian Affairs' water-development program for the Navajo Indians; by M. H. Miller, former engineer, Bureau of Indian Affairs; by C. M. Sells, superintendent, Navajo Tribal Water Development office; by J. M. Holmes, hydrologist, Navajo Tribe; by Buster Kingsley, supervisor of the Hopi Indians, Bureau of Indian Affairs; by the Navajo Tribal Council; and by other personnel of the Bureau of Indian Affairs and the Navajo and Hopi Indian Tribes connected with the well-development program.

PREVIOUS INVESTIGATIONS

Robinson (1913) mapped and described the volcanic rocks of the San Francisco volcanic field, which overlaps the southwestern part of the reservations. Emery

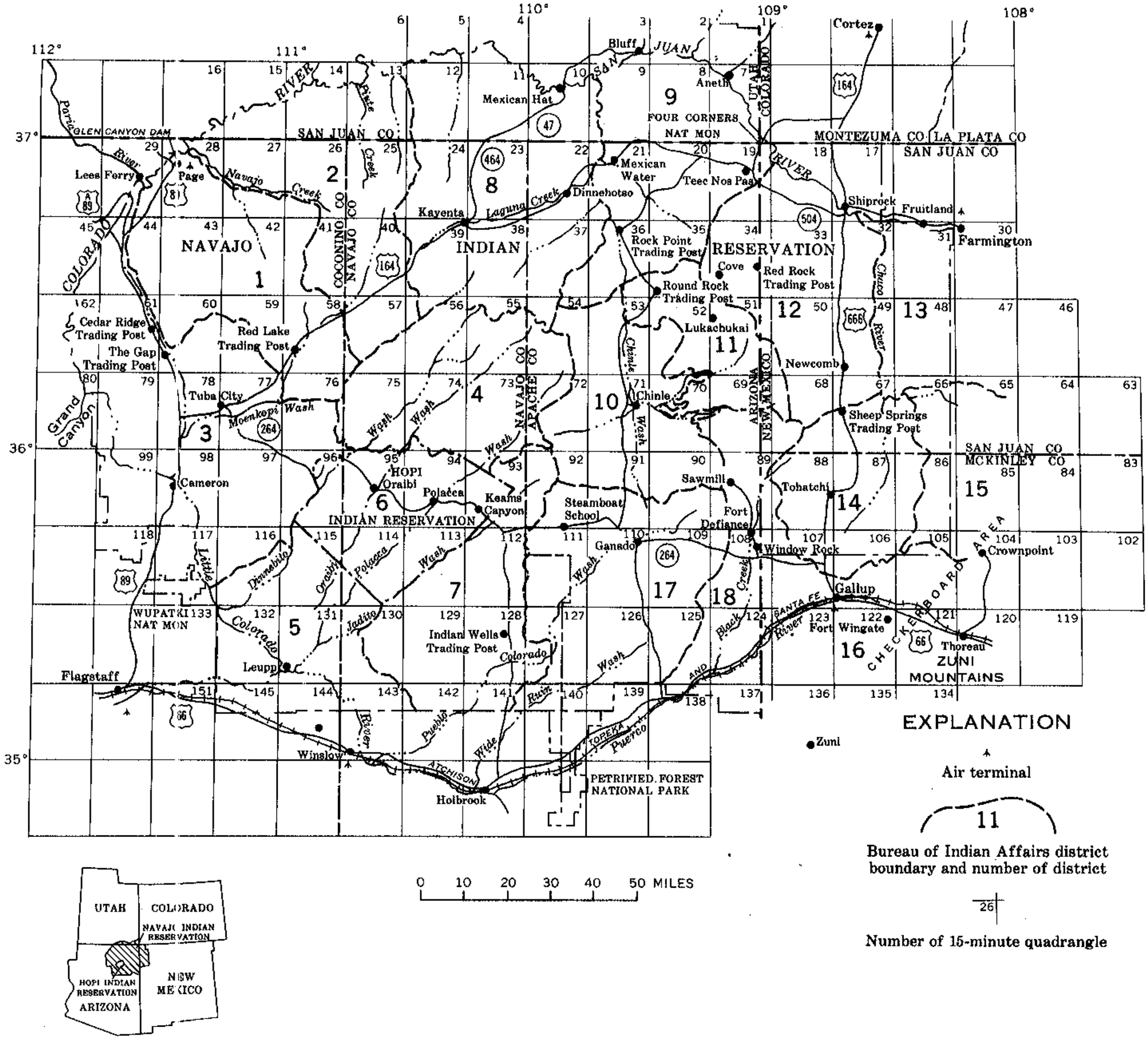

FIGURE 1.—Bureau of Indian Affairs administrative districts and 15-minute quadrangles.

(1916) studied the stocks, sills, and laccoliths in the Carrizo Mountains. Gregory (1917), Williams (1936), Hack (1942), Shoemaker (1956), Appledorn and Wright (1957), and Shoemaker, Roach, and Byers (1962) discussed the distribution, composition, origin, and emplacement of the volcanic rocks in the Navajo and Hopi Indian Reservations. Colton (1937) classified the flows and cinder cones in the San Francisco volcanic field on the basis of erosion and weathering, and Malde (1954) described the serpentine pipes at Garnet Ridge, Ariz. Callahan, Kam, and Akers (1959) discussed the occurrence of ground water in diatremes in the Hopi Buttes. Akers, McClymonds, and Harshbarger (1962) described the ground-water hydrology of the diatreme in Buell Park, which supplies part of the water used by the sawmill at Navajo, N. Mex.

STOCK LACCOLITHS

The Carrizo Mountains and possibly Navajo Mountain were formed as a result of igneous intrusion and updoming. Navajo Mountain appears to have resulted from a single intrusion. The Carrizo Mountains are a complex area composed of a central stock and offshoots of sills and laccoliths. The intrusives have affected the attitude of the surrounding sedimentary rocks only in the immediate area of the mountains and seem to be imposed on the regional structures—the Defiance uplift and the San Juan, Blanding, and Kaiparowits basins.

The Carrizo Mountains (pl. 1) are an irregularly shaped intrusive mass composed of a central stock and several sills that have been injected laterally into the surrounding sedimentary rocks. The mountains, rising 2,000–3,000 feet above the surrounding plain, are about 13 miles in diameter. Pastora Peak, at an altitude 9,420 feet above mean sea level, is the highest point in the mountains.

The Teec Nos Pos sill is the largest in the Carrizo Mountains and has a maximum thickness of about 300 feet. The sill is connected with the central core and dips 15° W. Several other sills cap mesas on the north side of the mountains. The sill rimming Black Rock Point (pl. 1) is the most northwestern protuberance from the central stock. Where exposed, it is a lens-shaped body 150–300 feet thick, which has been eroded to form a steep cliff. It is composed of a light-gray core having contorted and gnarled flowage lineation. The core is surrounded by a more resistant zone of dark-gray rock showing columnar structure that formed as a result of chilling.

The intrusive rocks are composed of light-gray diorite porphyry made up of abundant white plagioclase phenocrysts, smaller and less abundant hornblende phenocrysts, and sparse crystals of biotite and quartz set in a groundmass that, according to Emery (1916, p. 355–356), consists mainly of microgranular orthoclase and quartz. Accessory minerals are apatite, titanite, and zircon.

Navajo Mountain is a high slightly elliptical northeastward-trending dome that rises about 4,000 feet above the Rainbow Plateau and 10,416 feet above mean sea level. It has long been considered to be of laccolithic (concordant stock) origin (Gilbert, 1877, p. 69; Baker, 1936, p. 75; Hunt and others, 1953, p. 148), although igneous rocks were not found on the mountain until the 1960's (Condie, 1964, p. 359). The color and cementation characteristics of the Navajo and Dakota Sandstones exposed on the mountain are different than those exhibited by the sandstones in most outcrops; these differences probably indicate effects from intrusion of igneous rocks at depth. In several exposures the pale-reddish-brown Navajo Sandstone has been bleached to a light gray or white, and in places the generally calcareous cement of the sandstone has been replaced by siliceous material. The Dakota Sandstone, which caps the dome, is strongly silicified to a quartzite. Siliceous cementation and bleaching have taken place in the area near Copper Mine Trading Post and at Black Peak near Tuba City, as a result of igneous activity.

The igneous exposure on Navajo Mountain is a syenite porphyry that intrudes the Entrada Sandstone about 1½ miles southwest of the summit (Condie, 1964, p. 359). Inclusions of red sandstone and shale from Mesozoic formations or possibly older rocks are within the syenite. The contacts of the sedimentary rocks with the igneous body show little alteration or metamorphism.

The age of the stock-laccolithic intrusions of the Carrizo Mountains and Navajo Mountain is assumed to be the same as that of the Henry Mountains, which may range between "wide limits embracing a considerable part of Late Cretaceous time and practically all of Tertiary time" (Hunt and others, 1953, p. 90). No additional evidence pertaining to their age can be obtained directly from relations of these intrusions with the regional structural trends, basaltic volcanic rocks, Chuska Sandstone, Bidahochi Formation, or erosion surfaces.

The intrusive rocks of the Carrizo Mountains are known to yield water only to spring 12R–223. Cracks along the fractures in these rocks probably would yield small amounts of water, especially in the higher areas that receive considerable precipitation, but the dense unfractured part of the rocks precludes any movement of water.

The updoming of the Carrizo Mountains and Navajo Mountain has fractured the adjacent sedimentary rocks. In places, the Navajo Sandstone on Navajo Mountain is so fractured that it forms zones of shattered rock. These fractures facilitate recharge to and movement of water in the sandstone aquifers.

VOLCANIC ROCKS

The volcanic rocks in the reservations occur in widely separated volcanic fields. These rocks are composed entirely of ultramafic material. On the basis of composition, the volcanic fields can be grouped into three distinct, although related, provinces in the reservations—the minette province in the northeastern part, the monchiquite province centering chiefly in the Hopi Buttes (Shoemaker and others, 1962), and the basalt province in the extreme southwestern part (pl. 1).

Volcanic activity was concentrated in the northeastern, eastern, and southwestern parts of the reservations, but most eruptions occurred in the Hopi Buttes and San Francisco volcanic fields and in the several small volcanic fields in the Defiance Plateau-Chuska Mountains area (pl. 1). More than 300 vents are in the reservations, of which about 200 are in the Hopi Buttes volcanic field.

MONCHIQUITE PROVINCE

The monchiquite province includes the large Hopi Buttes volcanic field, centered approximately at the Dilcon Trading Post, and the small Tuba volcanic field near Tuba City (pl. 1). Table 1 lists the geologic and hydrologic properties of the volcanic rocks in the province.

The igneous rocks of the monchiquite province are dark dense lavas in which phenocrysts of augite and olivine, generally less than one-eighth of an inch long, are commonly recognizable; less commonly recognizable are phenocrysts of hornblende and biotite. Williams (1936, p. 124) stated: "Feldspar is nowhere visible to the unaided eye, and, indeed, in most of the rocks it is absent altogether." He described the lavas as having the general composition of monchiquite—limburgite, analcite basalt, trachybasalt, and olivine-augite basalt—and as differing only in minor constituents or in texture.

TABLE 1.—*Geologic and hydrologic properties of the volcanic rocks in the monchiquite and minette provinces*

Volcanic field	Location	Occurrence	Geologic properties and description	Hydrologic properties
Monchiquite province				
Tuba	Tuba Butte	Neck	Core of dense monchiquite encased in a sheath of peperites composed of compact sandstone, not bedded, stippled with monchiquite lapilli cut by thin curved sheets of lava; stands 300 feet above land surface.	No potential for development of ground water.
	Wildcat Peak	Neck and dikes	Monchiquite having a collar of pyroclastic debris; cut by several north-trending vertical dikes of tuff-breccia composed of fragments of monchiquite, mudstone, and sandstone; total length of dikes is 6 miles; adjacent strata updomed by the intrusion by more than 500 feet.	
	Dikes at Echo Cliffs, near Moenkopi Wash, and at Moenave	Dikes	Crumbly green monchiquite dike, 2 feet thick, that cuts across strata at Echo Cliffs; a porphyritic monchiquite dike (Barrington and Kerr, 1962), 1 to 10 feet wide and 2 miles long, along the base of Ward Terrace south of Moenkopi Wash, and an augite minette dike, 2 feet thick and 20 feet long, near Moenave.	
	Black Peak	Intrusive	Mainly Navajo Sandstone having thick coating of shiny black oxide of iron and manganese; a small intrusive body of monchiquite is in southern part (Barrington and Kerr, 1961); several small generally northwest-trending dikes; from a distance can be mistaken for a volcanic neck 400 feet high.	
Minette province				
Monument Valley	Agathla Peak	Neck	Tuff breccia and agglomerate composed of minette fragments of granitic, metamorphic, and sedimentary rocks; displays thin intersecting and branching dikes of minette cut through breccia and agglomerate in an erratic manner; mass held together by calcareous cement; stands more than 1,400 feet above the surrounding plain and more than 1,000 feet above pedestal composed of Chinle Formation.	No potential for development of ground water.
	Chaistla Butte and Church Rock	Necks	Necks are similar to Agathla Peak, consisting of brecciated minette and blocks of red sandstone as much as 20 feet in diameter; incorporated sedimentary rocks may constitute as much as half the total mass.	
	Alhambra Rock	Neck	Minette containing xenoliths of sandstone, limestone, and granite; neck is about 100 feet in diameter and merges with dikes that extend north and south.	
	Tse Ajai	Neck	Hornblende gabbro containing boulders of gray granite; an isolated neck about 200 feet in diameter that differs in composition from all other rocks in the minette province.	

TABLE 1.—*Geologic and hydrologic properties of the volcanic rocks in the monchiquite and minette provinces*—Continued

Volcanic field	Location	Occurrence	Geologic properties and description	Hydrologic properties
Minette province—Continued				
Monument Valley—Continued	Boundary Butte	Neck	Tuff-breccia and agglomerate; included fragments are shale, sandstone, limestone, minette, and plutonic and metamorphic rocks; most fragments are less than 1 foot in diameter, but a few minette fragments measure more than 3 feet across; the mass is cut by dikes of minette and held by calcareous cement; the neck is an elongate irregular mass 300 feet high and a quarter of a mile long; a large dike swarm, trending north-northwest to northeast, is nearby and probably is associated with the intrusion at Boundary Butte.	No potential for development of ground water.
	Near Boundary Butte and unnamed localities	Dikes	Same material as the neck; wallrock alteration is slight, but local bleaching and silicification are present; the dikes are from 2 to 50 feet wide and the longest one extends for 2 miles; some protrude as high as 60 feet above the land surface; most of the dikes are vertical, trend northwest, and are parallel to most anticlines and synclines but are at right angles to Comb monocline.	
	Garnet Ridge and unnamed localities	Diatremes	Breccia consisting of fragments that range from sand size to oval-shaped boulders as much as 20 feet long composed mainly of garnetiferous gneiss, schist, slate, quartzite, granite, red siltstone, and limestone with Paleozoic fossils; several diatremes contain blocks as much as 1,000 feet across composed of Jurassic sedimentary rocks; contain thin dikes of minette and light-green subsilicic igneous rocks intruded and altered to serpentine; diatremes are mainly in the Garnet Ridge area; surrounding area is strewn with wide variety of rock fragments brought up from depth; subsidence of 1,500 feet is demonstrated on the northeast end of diatreme forming Garnet Ridge (Malde, 1954, p. 618).	Some of the material in the diatremes may be sufficiently permeable to warrant test drilling.
Red Rock Valley	Mitten Rock and The Thumb	Necks	Minette with numerous xenoliths of sandstone, shale, and metamorphic and granitic rocks; at Mitten Rock assimilation of the granitic xenoliths by massive minette magma is evident.	No potential for development of ground water.
Chuska Valley	Ship Rock	Neck	Minette and tuff-breccia containing xenoliths of shale, limestone, sandstone, quartzite, granite, and diorite; mass is cut by branching and coalescing dikes of minette; neck stands 1,700 feet above the land surface and is more than a quarter of a mile in diameter; three large dikes and several small dikes of minette containing numerous granitic and diorite xenoliths radiate from the neck; the largest dike extends about 5 miles southward.	
	Barber Peak, Bennett Peak, and Ford Butte	Necks	Necks are similar to Ship Rock except that they contain few xenoliths.	
Chuska Mountains	Roof Butte	Neck	Vesicular trachybasalt, tuff-breccia, and agglomerate containing fragments as much as 6 inches in diameter composed of plutonic rock, dense and vesicular lava, and sandstone; lava and tuff cut by apophyses of minette; neck is the highest point on the Chuska Mountains—altitude, 9,576 feet.	
	At Washington Pass	Diatreme	Stratified tuffaceous agglomerate overlain by a vesicular flow of porphyritic trachybasalt; some thin dikelike masses of chalcedony and many vesicles and fractures in lava filled with calcite or chalcedony, possibly having been deposited from hydrothermal solutions; the diatreme is 2 to 2½ miles in diameter and several hundred feet deep.	Yields small amounts of water to three springs; perhaps some water would be obtained by test drilling.

TABLE 1.—*Geologic and hydrologic properties of the volcanic rocks in the monchiquite and minette provinces*—Continued

Volcanic field	Location	Occurrence	Geologic properties and description	Hydrologic properties
Minette province—Continued				
Chuska Mountains—Con.	Matthews Peak	Diatreme(?)	Stereoscopic examination of aerial photographs reveals that the thick columnar lava forming and underlying Matthews Peak dips inward, suggesting the presence of a diatreme.	No information available on hydrologic characteristics.
	13 miles northwest of Washington Pass	Volcanic depression (probably diatreme)	Tuffaceous agglomerate; depression is 2 miles long and 1 mile wide and is enclosed by Chuska Sandstone.	Spring 12GS-50-3 discharges from volcanic rocks in this structure.
	Beautiful Mountain	Sill	Minette, intruded into Chuska Sandstone; sill at Tsaile Peak is columnar jointed and a small dike extends west from the sill; sill is as much as 400 feet thick and has chilled borders.	No potential for development of ground water.
Wheatfields	Tsaile Peak	Neck	A "chimmneylike plug of columnar trachybasalt atop a cone of tuff-breccia and lava * * *" (Appledorn and Wright, 1957, p. 459–460).	
	3 miles east of Sonsela Buttes	Neck	Breccia and agglomerate; neck forms hub of three radiating dikes, another necklike mass is at northwest end of East Sonsela Butte.	
	Black Pinnacle	Neck(?)	Columnar jointed minette with inclusions of basalt, granite, and shaly sandstone.	
	Sonsela Buttes	Chiefly flows	Grayish columnar flows of trachybasalt; at least three flows as much as 100 feet thick cap Sonsela Buttes; "West Sonsela Butte is a circular, dome-shaped mass of lava capping a pyroclastic-filled crater * * *" (Appledorn and Wright, 1957, p. 459); a dike about 2 miles long is composed of slightly porphyritic minette on West Sonsela Butte.	
	The Palisades	Flow	Thick columnar wall of porphyritic trachybasalt, overlying tuff and tuff-breccia, that contains angular and rounded fragments of quartz, quartzite, granite, gneiss, sandstone, and mudstone; flow has a maximum thickness of 300 feet and is half a mile wide; it lies on an irregular surface having a relief of at least 1,200 feet (Appledorn and Wright, 1957, p. 454).	
Zilditloi	Zilditloi Mountain	Diatreme and flow	Trachybasalt lava containing abundant small xenoliths of granite, gneiss, quartzite, diorite, gabbro, and pyroxenite; Zilditloi Mountain is capped by a flat domelike mass of columnar dense to amygdaloidal trachybasalt; Allen and Balk (1954, p. 114) described this lava as having a faintly layered structure that dips into the mountain, inferring that the lavas may have been extruded from a funnel-shaped vent.	
	Fluted Rock	Neck(?)	Columnar jointed minette with numerous xenoliths of sandstone, shale, and granite; neck(?) is a flat-topped vertical-walled mass half a mile in diameter standing about 400 feet above surrounding land; Gregory (1917, p. 106) and Williams (1936, p. 139) believed it to be a laccolith, but Allen and Balk (1954, p. 112–114) stated it is a neck or plug.	
	Outlet Neck and The Beast	Neck and dikes	Central cores of blocky minette encased by breccia composed of blocks of lava, mudstone, and sandstone; granite xenoliths are sparse; breccia is cut by dikes of minette, locally altering the enclosing sandstone to buchite; composition of dikes at The Beast shows a transition of minette into monchiquite.	

TABLE 1.—*Geologic and hydrologic properties of the volcanic rocks in the monchiquite and minette provinces*—Continued

Volcanic field	Location	Occurrence	Geologic properties and description	Hydrologic properties
Minette province—Continued				
Zilditloi—Continued	Beelzebub	Neck and dike	Agglomerate containing fragments of minette as much as 3 feet in diameter and smaller fragments of sandstone and mudstone; two smaller pluglike masses of same composition, about 1 mile southwest of Beelzebub, which are widened parts of a dike that trends east and cuts through east flank of Zilditloi Mountain.	No potential for development of ground water.
	Green Knobs	Neck	Grayish-yellow lapilli tuff containing a variety of xenoliths concentrated on inward-dipping bedding planes; xenoliths generally are rounded and less than 1 inch in diameter, although a few measure 1 foot or more in diameter; xenoliths are composed of gneiss, granite, garnetiferous gneiss, sandstone, and shale; numerous chips of peridot and garnet; neck has weathered differentially into a group of low rounded knobs.	May obtain a small amount of water by test drilling.
	Buell Park	Diatreme	Green-gray lapilli tuff with small outcrop of kimberlite tuff; tuff contains olivine and garnet crystals and fragments of igneous and metamorphic rocks as well as angular and rounded pebbles of chert, quartzite, and slate; tuff is interbedded with cinders; circular depression of Buell Park probably is part of an eroded diatreme; depression is 2¼ miles in diameter and in places is 1,000 feet below the general level of the Defiance Plateau; Peridote Ridge is a talus-strewn curved vertical dike of columnar minette from 3 to 50 feet wide and about 2 miles long; Buell Mountain, capped by inward-dipping columnar trachybasalt, is an elongate complex of dikes and plugs rising to 1,000 feet above the floor of Buell Park.	At many horizons the tuff contains interbedded cinders, which greatly increase permeability, and wells penetrating these cinder beds may yield more than 500 gallons per minute; ground-water overflow from the tuff is discharged by springs into Buell Wash, a small tributary of Black Creek.
Twin Cones	Twin Cones	Necks	Tuff-breccia cut by numerous branching dikes of minette; the breccia consists of broken sandstone with lesser amounts of fragmental minette, alaskite, quartz porphyry, and mudstone; these two necks intrude rocks of the Mesaverde Group containing coal only slightly affected by the intrusions.	No potential for development of ground water.
	Black Rock near Fort Defiance	Neck	Minette and agglomerate composed of fragments of sandstone, mudstone, and igneous rocks; elongate neck standing about 200 feet high.	No potential for development of ground water.

The dark volcanic rocks of the Hopi Buttes volcanic field stand out in sharp contrast against the surrounding multicolored sedimentary rocks, and they occur as lava flows in and capping mesas, as exposed necks and diatremes of different heights and shapes, as wall-like dikes, and as beds of pyroclastic material. The largest expanse of lava, at Hauke Mesa near the Indian Wells Trading Post, is about 11 miles long and 3 miles wide (pl. 2).

The lava flows and associated tuff beds constitute the volcanic member of the Bidahochi Formation (Repenning and Irwin, 1954, p. 1823); the volcanic member is stratigraphically between the upper and lower members of the Bidahochi. The diatremes and dikes cut through the lower member and the older rocks, and the flows and pyroclastic material lie below and are interbedded with the basal part of the upper member of the Bidahochi.

Diatremes (pl. 2) have long been recognized as the most interesting feature of the Hopi Buttes volcanic field, and in places they furnish a dependable water supply. The diatremes probably were formed by phreatic explosions created by the conversion of water to steam, which, in turn, expelled tuff and agglomerate. This initiated a cycle that ended when upwelling lava pushed the tuff and agglomerate from the vent and then spread over the surface in flat or dome-shaped flows; this cycle was not completed for all vents, and only agglomerate and tuff are present in some vents. In some diatremes subsidence has caused the beds to dip inward toward the vent. In a small diatreme southeast of Little Twin Buttes, a large block of Wingate Sandstone in the material filling the vent is 100 feet below the base of the Wingate. The funnellike shape of many of the vents may have been caused by the initial explosive action, but subsidence may have enlarged many of the vents by partial withdrawal at depth of the magma that filled them.

The vent filling is monchiquite lava, tuff, and agglomerate, or combinations of these materials, depending on how far the cycle had progressed when volcanism ceased. Diatremes in which the cycle was completed are represented by lava flows and by necks of monchiquite where erosion has removed the overlying and surrounding materials. Montezumas Chair is representative of a diatreme in which the cycle was completed. In diatremes in which the cycle was partly completed, the fill is coarse tuff-breccia and agglomerate, which, in some places, is penetrated by thin monchiquite dikes. In most of the Hopi Buttes area, vents filled with the tuff-breccia and agglomerate form shallow bowl-shaped topographic features that reflect the funnel shape of the orifice. Commonly, the tuff-breccia and agglomerate are overlain by thin-bedded marly clay, siltstone, and tuffaceous sandstone.

The amount of lava or tuff present determines the water-bearing characteristics of the material in the diatreme. Test-drilled diatremes containing water are filled mainly with tuffaceous material, and those containing little or no water are filled with lava.

Impure travertine and small amounts of chert are associated with the igneous rocks of the Hopi Buttes volcanic field and may have been deposited during the course of the volcanism or shortly afterward. The travertine is found in and about spring orifices in diatremes, in irregular lenses in lava flows, and in irregular beds interlaid with tuff. Most of the travertine probably was deposited from ground water that had moved upward in the vent from the Coconino Sandstone of Permian age, which is the main aquifer in the area.

The thickness of the lava flows in the Hopi Buttes area is extremely variable—25 to a few hundred feet—because the flows are dome shaped and commonly overlap. The thickness of the lava capping a single mesa may differ as much as 100 feet in a distance of 1,000 feet. The lava generally flowed out on porous tuff and agglomerate that rest on mudstone-siltstone beds of the lower member of the Bidahochi Formation. The tuff beds form a conspicuous spring horizon around Hauke Mesa, and elsewhere yield water to isolated springs (pl. 2).

The volcanic rocks of the monchiquite province are considered to be Pliocene in age because they are interbedded with the Pliocene Bidahochi Formation (Williams, 1936; Hack, 1942). The monchiquite deposits of the Hopi Buttes volcanic field, grouped together as the volcanic member of the Bidahochi Formation, are between the fossiliferous lower and upper members of the Bidahochi, which, according to Lance (1954), are of late Miocene(?) to lower Pliocene and middle Pliocene age, respectively. Because the middle volcanic and upper members are associated closely in deposition, the volcanism is believed to have occurred principally during middle Pliocene time. Support for a late to middle Pliocene age for the volcanic rocks is indicated from a potassium-argon age determination of 4.1 million years (Evernden and others, 1964, p. 164) obtained from the flow on the south side of Roberts Mesa.

MINETTE PROVINCE

Volcanic rocks of the minette province are distributed throughout the Navajo country north and east of the Hopi Buttes volcanic field (pl. 1). They occur in widely spaced volcanic fields—Monument Valley, Red Rock Valley, Chuska Valley, Chuska Mountains, Wheatfields, Zilditloi, and Twin Cones (Gregory, 1917; Williams, 1936)—and as isolated necks, dikes, and dike swarms (pl. 1). Descriptions of many necks, diatremes, and flows are given in table 1.

The volcanic rocks of the minette province are distinguished from those of the monchiquite province by a slight difference in composition and by the incorporation of many plutonic xenoliths in the intrusives and extrusives. The mineral composition of the minette is characterized by biotite and subordinate diopside phenocrysts in a groundmass of orthoclase or sanidine.

Most of the diatremes of the minette province have been deeply dissected and now are represented by necks throughout the area. Williams (1936, p. 131) divided the volcanic rocks of the Navajo country into two groups, on the basis of the amount of postvolcanic Cenozoic erosion of the necks or vents, which roughly correspond with the minette and monchiquite provinces—the Hopi field, where surface features are associated with the vents, and the Navajo field, where erosion has removed the surface features associated with the vents. As a result of the erosion, flows in the minette province remain only in the Chuska Mountains area. Some of the necks, such as Agathla Peak and Ship Rock, form conspicuous monuments, which stand 1,000 feet or more above the surrounding country. Other necks, such as The Beast in the Zilditloi volcanic field, are less than 200 feet high. With few exceptions, all the necks contain xenoliths of granite, gneiss, schist, or diorite. In some, such as in The Thumb east of the Red Rock Trading Post, xenoliths constitute about 10 percent of the total mass, but in others, such as in Bennett Peak and Ford Butte, xenoliths are rare. The largest known xenolith, 20 by

30 by 50 feet, is derived from the Chuska Sandstone and is exposed in a neck 4 miles northeast of the Round Rock Trading Post. The xenolith now rests about 2,500 feet below the base of the Chuska Sandstone. Mitten Rock, a neck about 4 miles northeast of the Red Rock Trading Post, consists largely of massive igneous material, but other necks, such as Boundary Butte and Beelzebub, consist of tuff-breccia and agglomerate, cut in places by dikes of minette.

Dikes are slightly more conspicuous in the minette province than in the monchiquite province. They generally form conspicuous black walls; some of the dikes stand more than 100 feet above the land surface and extend for several miles. The dikes generally trend northwestward and subparallel to most axes of anticlines and synclines. Nowhere in the minette province—or in the monchiquite province—has the emplacement of the dikes disturbed the enclosing sedimentary rocks.

The diatremes at Buell Park and at Washington Pass are large features more than 2 miles in diameter and are known to discharge some ground water. The diatreme at Washington Pass has not been eroded severely and shows inward-dipping beds, but the upper part of the diatreme in Buell Park has been removed by erosion, leaving only a circular depression more than 2 miles wide and about 500 feet deep that is underlain by volcanic material (fig. 2).

The diatreme at Buell Park is composed principally of well-consolidated lapilli tuff. The tuff is gray green and contains fragments of igneous rocks and angular to rounded fragments of material derived from the country rock at depth. Most of the fragments consist of chert, quartzite, and slate; a few are composed of granite. The matrix is tuffaceous and contains abundant olivine and garnet crystals. At many levels the tuff contains interbedded cinders, which greatly increase the permeability. Minette or trachybasalt has intruded the tuff and occurs as necks and dikes. One unusual feature in Buell Park is a ring dike that rises about 100 feet above the floor of the park (fig. 2); another is a small plug that was identified by Allen and Balk (1954) as having the composition of kimberlite.

During the development of the diatreme, several explosions occurred that spread olivine, garnet, and diopside minerals. Minerals common in Buell Park and also in the Green Knobs are found as lag material in a radius of 9 miles from the park. Lapilli tuff and cinders were erupted, and lenses of this material presently dip 15° to 30° into the park. Later, basaltic dikes, flows, and necks were emplaced, and the area was eroded. The less resistant tuff was removed faster than the basaltic intrusive rocks, which now protrude above the floor of the circular depression.

The diatreme at Washington Pass is outlined by an inward-dipping vesicular flow of porphyritic trachybasalt overlying stratified tuffaceous agglomerate. Three closely spaced, necklike, conical hills, which are composed of porphyritic tuff and are intruded and capped by porphyritic trachybasalt, rise about 400 feet above the floor between the center of the diatreme and its eastern rim. The two northernmost hills are cut by dikes of coarse trachybasalt. Several low mounds of vesicular lava occur on the floor of the crater north of these hills. The mounds are cut by many branching veins of chalcedony, and in places the surface of the mounds is covered with botryoidal layers of chalcedony. In several exposures in creek bottoms, vesicular lava identical with that of the mounds is exposed, and it is possible that the lava underlies a major part of the crater floor.

According to D. L. Zieglar (geologist, U.S. Geological Survey, written commun., 1953), two periods of explosive activity, each followed by extrusion of lava, are represented at Washington Pass. The first extrusion of lava was followed by collapse, which was followed later by more explosions and a second extrusion of lava represented by the lava capping the three conical hills. The sequence of events, summarized from Appledorn and Wright (1957, p. 453–454), consisted of (1) explosive activity that produced ash and lapilli, (2) deformation accompanied and followed by explosive eruptions, (3) relatively quiet extrusion of trachybasalts, (4) subsidence estimated at 300 feet and enlargement of the conduit accompanied by lava outpourings, and (5) extrusion of the rubble dome that was intruded by plugs and dikes of minette, forming the three conical hills.

The ages of the volcanic rocks in the minette province are not known precisely, and they may span a considerable length of time. Williams (1936) believed that the rocks may have erupted more or less contemporaneously with those of the Hopi Buttes volcanic field, which are Pliocene in age. However, an isotope age date of 31 million years (Oligocene) was reported by Pye (1967, p. 81) for a sill that is intruded into rocks of Pennsylvanian age in the northern part of the Chuska (Lukachukai) Mountains. The sill is considered by J. D. Strobell (oral commun., 1968) as similar to the volcanic rocks of the Navajo country called minette by Williams (1936), although several investigators have called the sill syenite. Isotope age determinations on this sill made by the U.S. Geological Survey Laboratory, Denver, Colo., on the sanidine and biotite indicated ages of 41 and 25 million years, respectively. The apparent differences in the ages and an indicated age which is older than is generally believed by most investigators are

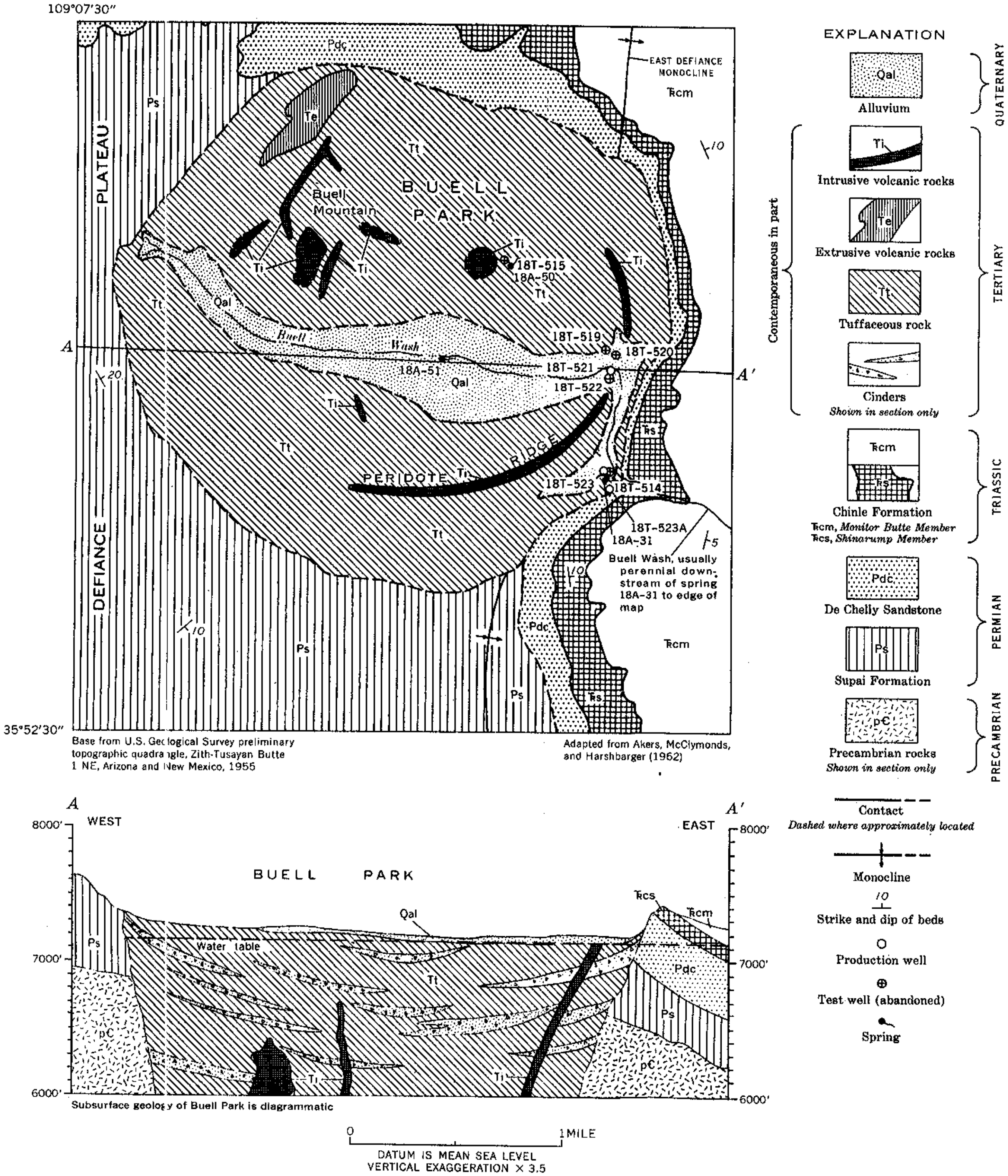

FIGURE 2.—Geologic map and section of the diatreme in Buell Park, showing the ground-water conditions, northeastern Navajo Indian Reservation, Ariz.

probably due to excess radiogenic argon in the sanidine and possibly in the biotite (J. D. Strobell, oral commun., 1967). Volcanic rocks of the minette province have intruded the Chuska Sandstone and, therefore, are younger than the Chuska. The Chuska Sandstone cannot be dated accurately, although the Geological Survey considers it to be very early Pliocene(?) in age. Most investigators consider the Chuska Sandstone to be Oligocene or Miocene in age (Wright, 1956, p. 427–432; Cooley and others, 1967). In any case, the Chuska is older than the Bidahochi Formation, which contains fossils of early Pliocene age. On the basis of erosional history, the volcanic rocks in the minette province could be significantly older than those in the Hopi Buttes (M. E. Cooley, oral commun., 1954; R. L. Sutton, written commun., 1968).

BASALT PROVINCE

The volcanic rocks of the basalt province are represented by flows and several cinder cones that constitute only the northeastern part of the San Francisco volcanic field (pl. 1). Robinson (1913, p. 38 and pl. 3) outlined three general periods of eruption in the San Francisco volcanic field and mapped the igneous rocks according to the period in which they were erupted. The first- and third-period lavas are olivine basalt of almost identical composition and appearance. The second-period lavas range in composition from andesite to rhyolite. Only lavas of Robinson's third period are present in the Navajo Indian Reservation. Colton (1937) subdivided the basalt (first and third periods of Robinson, 1913) of the San Francisco volcanic field into five stages based on the amount of erosion and weathering of the basalt cinder cones and flows. The flows of the San Francisco volcanic field were related by Childs (1948) and Cooley (1962) to the levels of the erosion surfaces formed in the valley of the Little Colorado River.

The Stage I flows of Colton (1937) overlie the Black Point surfaces (Black Point peneplain of Gregory, 1917) on bluffs along both sides of Tappan Wash southwest of Cameron, on a mesa due south of Grand Falls, and on Black Point, a conspicuous landmark in the valley of the Little Colorado River (pl. 1). All the Stage I flows are at altitudes of more than 500 feet above the streambed of the Little Colorado River and lie on the divides between the tributary streams.

The basalt of Colton's (1937) Stages II and III is on the Wupatki surfaces (Childs, 1948) and is between 100 and 300 feet above the Little Colorado River channel. The lavas of Stage II must have been extremely fluid because flows more than 15 miles long are common. At least two Stage II flows formed barriers across and diverted the flow of the Little Colorado River. One lava flow dammed an ancestral channel of the river about 6 miles southeast of Grand Falls. The other flow entered the canyon of the Little Colorado River at the mouth of Tappan Wash and flowed downstream for 5 miles. This flow, the longest recorded in the San Francisco volcanic field, extends for more than 30 miles (Colton, 1937, p. 22).

Although there are many Stage III cinder cones and vents in the northeastern part of the San Francisco volcanic field, only a few, in the area south of Grand Falls and at Shadow Mountain, are within the confines of the reservations. Little dissection has occurred on Stage III flows and cones. Many flows, especially those near the cinder cones, are covered by a mantle of unconsolidated cinders. The cinders have been transported by wind, and dunes composed of the cinders form a discontinuous cover in a wide area west of Leupp.

The Stage IV and Stage V lavas make up a minor part of the San Francisco volcanic field. Some of the Stage IV flows were highly fluid, and one dammed the Little Colorado at Grand Falls and extended downstream to Black Falls (pl. 1). At Grand Falls the main body of the lava filled the river channel, which was excavated into the Kaibab Limestone. Subsequently, the river altered its course to circumvent the flow (Robinson, 1913, p. 17–18), and Grand Falls, 125 feet high and 400 feet wide, was formed at the point where the river reenters the canyon on the downstream side of the lava. Downstream near Black Falls the lava spread out in the valley and forced the river to reestablish its course over the lava. No lava of Stage V is present in the reservations; the eruptions of this stage occurred only at Sunset Crater 15 miles northeast of Flagstaff, Ariz.

The basaltic lavas of the San Francisco volcanic field near the Little Colorado River help record the late Pliocene and Quaternary development of the valley of the Little Colorado River (Cooley, 1962). The Stage I lavas overlying the Black Point surfaces are late Pliocene and early Pleistocene in age. Stage II and Stage III lavas overlying the Wupatki surfaces range from middle(?) to late Pleistocene in age. The Stage IV eruptions flowed in channels cut below the youngest Wupatki surface and are overlain by late Holocene alluvium. The age of the Stage IV flows is late Pleistocene to early Holocene. Stage V lavas, represented only by Sunset Crater, and two associated flows have been dated by dendrochronological and archaeological methods as late Holocene, with the main(?) or latest(?) eruption of the crater occurring about A.D. 1065 (Smiley, 1958, p. 190).

HYDROLOGY OF THE VOLCANIC ROCKS

The volcanic rocks are utilized as a source of ground water in parts of the Hopi Buttes, in Buell Park, and at a few other places in the reservations. In the Hopi Buttes area, 38 springs and one dug well (Davis and others, 1963) discharge water from the volcanic rocks and from spring deposits associated with the volcanism. In other parts of the reservations, 11 springs yield a small amount of water from isolated exposures of volcanic rocks. By 1968, 14 diatremes in the Hopi Buttes area had been tested by drilling, and some water was found in 11 of the diatremes. Wells withdraw moderate amounts of water from the fill of the diatreme that forms Buell Park. The wells and springs that obtain water from the volcanic rocks are shown on plates 1 and 2.

Recharge to the volcanic rocks is mainly from the precipitation that falls on the outcrops. The mean annual precipitation generally is less than 10 inches in the parts of the reservations where the volcanic rocks are exposed, except in the Defiance Plateau–Chuska Mountains area where it is more than 15 inches per year. In places, additional recharge occurs from small ephemeral streams that flow across diatremes and lava flows.

Movement of ground water in most of the volcanic rocks is restricted to the limited extent of their outcrops and takes place mainly along fractures in the lava flows, tuff beds underlying the flows, and tuffaceous units in diatremes. The only area where ground water moves laterally for more than 1 mile is in the flows and tuff beds capping Hauke Mesa in the Hopi Buttes. Here, water percolating into fractured lava moves downward into tuff beds that form the basal part of the volcanic sequence. The tuff beds are underlain by sedimentary rocks having a low permeability, and the water moves laterally along the basal contact of the tuff beds and discharges as springs or seeps along the sides of the mesa (pl. 2).

The quantity of water that discharges from the volcanic rocks is small, and, based on discharge measurements of springs (Davis and others, 1963), the combined yield of these rocks is about 125 gpm (gallons per minute). Nearly half this yield, however, is from spring 18A–31 in Buell Park; this spring flows at a rate of about 60 gpm. Considerably more water probably seeps out and is evaporated at the edges of the volcanic outcrops, mainly in places where lava flows are underlain by nearly impermeable sedimentary rocks. Seepage areas are indicated along the outer edges of many flows by thickets and lines of brush. In the Chuska Mountains some of the water in the flows and diatremes aids in recharging the Chuska Sandstone; in the Hopi Buttes, particularly west and southwest of Hauke Mesa, where the volcanic rocks are in contact with the Wingate Sandstone, Bidahochi Formation, and alluvium, some water discharges from the volcanic rocks into these formations.

The 38 springs in the Hopi Buttes area discharge mainly from the thin tuff beds beneath the lava flows and from the tuffaceous material filling diatremes. The springs are the discharge points for water moving along bedding planes in and along the basal contact of the tuff beds and along fractures in all materials that compose the volcanic rocks. In 1954 when the springs were visited (Davis and others, 1963), they flowed at a combined rate of about 20 gpm. Six of the springs discharged at a rate of 1 gpm or more, and only springs 7H–161 and 7K–303 flowed at a rate of 3 gpm; however, 20 springs flowed at a rate of 0.2 gpm or less. Spring 7H–172 was dry when visited in 1954, but it had a reported yield of about 0.8 gpm in August 1924.

Fractures in the volcanic rocks in widely separated areas in the Chuska and Carrizo Mountains yield some water to six springs. The aggregate rate of flow of the springs is about 20 gpm. Of this total, 10 gpm is from spring 12GS–50–3, and 4 gpm is from spring 14N–108; both springs are in the Chuska Mountains. Relatively plentiful recharge is available to these rocks because they crop out at an altitude of more than 8,000 feet and receive at least 20 inches of precipitation per year. Although repeated discharge measurements of the springs are not available, the flow probably fluctuates seasonally, especially in years having high snowfall.

The Tappan lava flow (pl. 1) is the only unit of the San Francisco volcanic field that is known to yield water within the Navajo Indian Reservation. Well 3T–501 was drilled into the flow a short distance south of spring 3A–58, which furnishes water to Cameron. The spring discharges a small amount of water from the flow in combination with gravel beneath the flow and the Shinarump Member of the Chinle Formation. The yield may be as much as 20 gpm, but during dry periods, when little recharge occurs, it is less than 5 gpm. Well 3T–501 was bailed at an average rate of 4 gpm for only half an hour. During the test, the hole was bailed dry, and the water level in the well was lowered from 67 feet below the land surface to 92 feet, the depth of the well. The well was abandoned because of its low yield and because continued pumping might have dried up spring 3A–58.

DIATREMES

The diatremes are unique traps for the accumulation of ground water, although they have relatively small recharge areas and most are in the Hopi Buttes where the amount of precipitation is small. The general funnel shape of the structures provides maximum recharge surfaces, and the inward-dipping beds promote centripetal movement of water. The explosive action and subsidence that took place when the diatremes were formed evidently fractured the material in the diatremes and the sedimentary rocks in the immediate vicinity; therefore, they have a relatively high secondary permeability.

Near the surface, most of the diatremes in the Hopi Buttes are surrounded by sedimentary rocks composed of claystone to very fine grained silty sandstone. These rocks have a low permeability, which retards most underflow losses of water that enters the diatreme. The bedded tuff and agglomerate have the highest permeability of any material filling the diatremes and are also more permeable than the surrounding rocks, except the Coconino Sandstone, which is more than 2,000 feet below the land surface. If the material in the diatremes is sufficiently permeable at depth, then it is conceivable that some of the downward-moving ground water discharges into the Coconino Sandstone.

Of the 14 test wells drilled into the material filling the diatremes in the Hopi Buttes area, only wells 7K-367, 7T-522, 6-1-F-9, and P. M. 2 Dilcon are known to yield more than 10 gpm (table 2). In three wells the water was unfit for domestic or stock use or the wells were bailed dry during short-term tests; three wells were dry. Well P. M. 2 Dilcon was reported to yield more than 100 gpm with less than 1 foot of drawdown, and well 7T-522 was tested at an average bailing rate of 36 gpm and had a drawdown of 6 feet. The wells that produced water are from 85 to about 820 feet deep, and the static water levels in these wells are between 30 and 197 feet below the land surface.

In the Defiance Plateau–Chuska Mountains area, relatively permeable sedimentary rocks are in contact with the diatremes at and near the land surface. The diatreme at Washington Pass was emplaced in the Chuska Sandstone, one of the aquifers in the reservations. The material in this diatreme and the nearby Chuska Sandstone have not been test drilled, and their water-bearing potential is not known. The De Chelly Sandstone and the alluvium are in contact with the material filling the diatreme at Buell Park. The De Chelly Sandstone is one of the major aquifers in the reservations, and the material in the diatreme, the alluvium, and the De Chelly Sandstone form a multiple-aquifer system (fig. 2).

TABLE 2.—*Records of wells drilled in diatremes in the Hopi Buttes volcanic field*

[R, reported]

Quadrangle	Well	Depth of well (feet)	Water level (feet)	Yield (gallons per minute)	Drawdown (feet)	Specific capacity (gallons per minute per foot of drawdown)
93	6-1-F-9	301	212	11	0	------
111	17T-540	85	30	5	40	0.12
112	7T-511	220	135 R	5	85	------
	7T-513	380	170 R	20	210	------
	7T-514	370	Dry	------	------	------
128	7K-367	522	191	18	None	------
	7T-510	875	74	15	300	------
	7T-516	415	197 R	8	218	------
	7T-523	87	Dry	------	------	------
	Indian Wells P. M. 2	820 R	30	------	------	------
129	New Mexico-Arizona Uranium Co.	293	173	------	------	------
	7T-522	150	74	36	6	6.0
	7T-524	305	Dry	------	------	------
	Dilcon P. M. 2	202	98	100+	.2	------

Two production wells were completed in the crudely bedded lapilli tuff and interbedded cinders that fill the diatreme at Buell Park. Well 18T-514 (fig. 2) was drilled into the lapilli tuff and yielded 174 gpm for 72 hours with a drawdown of 50 feet from a static water level of 21 feet. The test indicated a specific capacity of 3.5 gpm per foot of drawdown. Well 18T-521 penetrated a cinder zone interbedded with the tuff between 50 and 70 feet. The well was drilled to a total depth of 115 feet. In a 72-hour pumping test it yielded 625 gpm with a drawdown of 28.5 feet from a static water level of 31.5 feet. The specific capacity computed from this test is 21.9 gpm per foot of drawdown, which indicates that the well is one of the best in the Navajo country.

Well 18T-521 was deepened to 250 feet, and another pumping test was made. The well was pumped for about 8 days at an average rate of 550 gpm, which caused a drawdown of 16.25 feet below the static water level that stood at 28.45 feet below the land surface before the test. The specific capacity determined from the test is 34.5 gpm per foot of drawdown, showing that the yield of the well had been increased. The well was then pumped for 1¾ days at a rate of 1,200 gpm; during this time, the pumping level lowered an additional 68.30 feet—to 113.0 feet below the land surface—making a total drawdown of 84.55 feet. The specific capacity determined from this test was only 14.2 gpm per foot of drawdown.

Results of pumping tests in Buell Park indicate that the lapilli tuff is moderately permeable and yields a larger quantity of water to wells than the surrounding sedimentary rocks—the De Chelly Sandstone and Supai Formation. The range of specific capacity computed from the tests is between 3.4 and 34.5 gpm per foot of drawdown. The tests also indicate that the permeability of the tuff may decrease with depth and that the highest yield probably is from a cinder zone 50–70 feet below the land surface (well 18T-521). The differences in the specific capacities suggest that the distribution of the cinder beds in the tuff deposits forms a chief control on the yields from wells drilled in the volcanic material.

The spacing of the test wells also indicates that the most permeable material is near well 18T–521 in the east-central part of the diatreme (fig. 2).

CHEMICAL QUALITY OF THE GROUND WATER

The chemical quality of the water in the volcanic rocks of the Navajo country differs widely from place to place. This difference is shown best in water from wells drilled in the material filling the diatremes in the Hopi Buttes area. The dissolved-solids content of the ground water in five diatremes in the Hopi Buttes and the one in Buell Park ranges from 262 to 8,140 ppm (parts per million). In contrast, the concentration of dissolved solids in water discharging from springs in the other volcanic rocks ranges from 246 to 1,450 ppm. Table 3 gives chemical analyses of water from the volcanic rocks.

The main constituents in the water from wells are sulfate, sodium, and chloride, which are present in concentrations of as much as 5,270, 2,230, and 1,810 ppm, respectively. The amount of bicarbonate is relatively small, probably no more than 662 ppm. Two wells drilled in the diatremes, 7K–367 and 7T–510, contain water having more than 1.5 ppm fluoride, the uppermost limit as established by the U.S. Public Health Service (1962) that will not cause mottled enamel in the teeth of children.

The concentrations and types of the constituents in water obtained from the wells drilled in diatremes probably are controlled largely by the soluble material embedded in the fillings of the diatremes. Bedded gypsum and selenite crystals are abundant in some of the diatremes. Many of the diatremes contain traces of uranium-bearing minerals, and several contain significant amounts. A small amount of uranium ore was mined from the fill of diatremes in the Hopi Buttes in 1954–57. The uranium ore minerals are relatively soluble in water and may have contributed substantially to the dissolved solids in the mineralized water in some of the diatremes.

The water from springs discharging from the volcanic rocks in the Hopi Buttes and from the diatreme in Buell Park is similar in chemical quality to that of most springs discharging from the sedimentary rocks in the reservations. The water has less than 1,500 ppm dissolved solids and is generally high in bicarbonate and low in sulfate, chloride, and sodium.

DEVELOPMENT OF GROUND WATER

Additional development of water supplies from the volcanic rocks is limited principally to the diatremes in the Hopi Buttes. Only 13 of about 25 accessible diatremes have been tested for water; the rest may contain sufficiently permeable material to yield some water to wells. However, the chemical quality may be so poor in some that the water will be unfit for human consumption or even for stock use. Some of the diatremes that may yield water to drilled wells are shown on plate 2.

TABLE 3.—*Selected chemical analyses of the ground water in the volcanic rocks*

[Analyses in parts per million, except as indicated]

Quadrangle	Well or spring	Location	Temperature (°F)	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na+K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids		Hardness as $CaCO_3$		Percent sodium	Sodium-adsorption ratio (SAR)	Specific conductance (micromhos at 25°C)	pH	Remarks
														Parts per million	Tons per acre-foot	Calcium magnesium	Noncarbonate					
Drilled wells																						
89	18T-514	Buell Park	54	25	24	45	90	347	0	120	19	0.3	4.3	499	0.68	245	------	44	2.5	791	8.2	Lapilli tuff filling diatreme.
	18T-521A	do	------	36	20	52	(1)	314	0	75	11	.1	0	394	.54	265	8	20	.9	624	7.8	Do.
112	7T-511	Hopi Buttes	------	11	43	23	1,060	142	0	2,270	21	.5	1.5	3,500	4.76	202	86	92	33	4,650	7.8	Diatreme.
	7T-513	do	58	37	58	72	275	456	0	602	25	.8	2.5	1,300	1.77	440	67	58	5.7	1,840	7.8	Do.
128	7K-367	do	64	------	------	------	423	662	8	296	58	2.8	.2	------	------	33	0	97	32	1,790	8.4	Do.
	7T-510	do	73	16	360	22	2,230	82	0	5,270	202	2.7	1.2	8,140	11.1	988	922	83	31	9,420	7.9	Do.
	7T-516	do	------	24	140	127	1,840	188	0	2,080	1,810	.9	.5	6,110	8.31	872	718	82	27	8,790	7.8	Do.
129	7T-522	do	------	24	15	17	55	221	0	19	10	1.0	12	262	.36	108	0	52	2.3	452	7.6	Do.
Springs																						
32	12R-80	Chuska Valley volcanic field.	64	15	6.5	1.1	313	225	0	332	120	0.8	0.4	900	1.22	20	0	97	30	1,450	------	Intrusive.
49	12R-103	do	63	24	5.6	2.3	311	314	0	351	51	1.5	.9	901	1.23	24	0	97	28	1,350	------	Do.
50	12GS-50-3	Chuska Mountains.	58	37	38	6.8	2.1	141	0	4.7	2	.2	4.1	164	.22	123	8	4	.1	246	------	Do.
98	3A-58	Cameron	64	25	57	30	30	195	0	134	10	.5	20	403	.55	266	106	20	.8	602	------	Tappan flow.
112	7H-63	Hopi Buttes	70	19	9.0	5.0	71	162	0	21	16	.4	25	246	.33	43	0	78	4.7	390	------	Tuff and spring deposits.
113	7H-179	do	64	27	39	24	55	265	0	70	16	.3	1.2	362	.49	196	0	38	1.7	375	------	Do.
128	7H-158A	do	------	31	41	39	41	395	0	11	5	.1	11	373	.51	263	0	25	1.1	619	------	Do.
	7K-303	do	60	17	4.0	1.4	250	465	0	118	37	.8	.6	658	.89	16	0	97	27	1,050	------	Do.
129	7H-183	do	56	33	45	16	63	317	0	24	19	.4	4.1	360	.49	178	0	44	2.1	569	------	Do.

[1] Sodium, 32 ppm; potassium, 14 ppm.

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